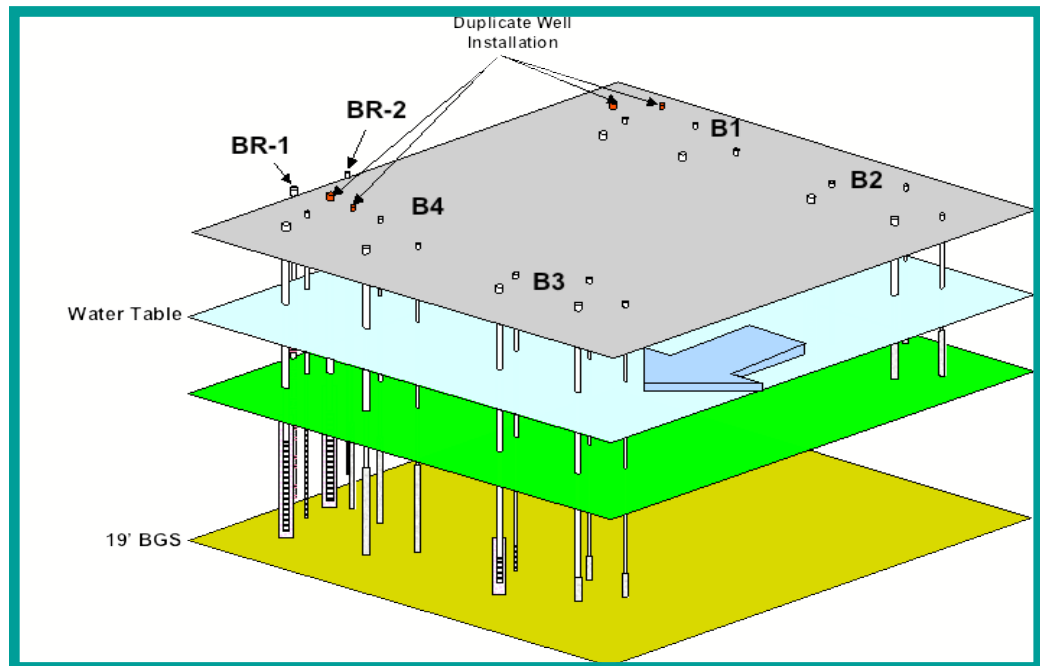


# ESTCP Cost and Performance Report

(ER-0011)



## Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct Push Technologies

March 2008



ENVIRONMENTAL SECURITY  
TECHNOLOGY CERTIFICATION PROGRAM

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# **COST & PERFORMANCE REPORT**

## **ESTCP Project: ER-0011**

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## ACRONYMS AND ABBREVIATIONS

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AFB	Air Force Base
AFRL	Air Force Research Laboratory
ANOVA	Analysis of Variance
ASTM	American Society of Testing and Materials
BGS	below ground surface
BTEX	benzene, toluene, ethyl benzene, xylene
CPT	Cone Penetrometer Testing
CRREL	Cold Regions Research and Engineering Laboratory
DNAPL	Dense Non-Aqueous Phase Liquid
DNTS	Dover National Technology Site
DoD	Department of Defense
DOE	Department of Energy
DP	direct push
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology and Certification Program
HAFB	Hanscom Air Force Base
HASP	Health and Safety Plan
HSA	hollow stem auger
IDW	industrial derived waste
ITRC	Interstate Technology and Regulatory Council
LIF	laser-induced fluorescence
LTM	long-term monitoring
MTBE	methyl tertiary butyl ether
NAPL	non-aqueous phase liquid
NBVC	Naval Base Ventura Complex
NETTS	National Environmental Technology Test Site
NFESC	Naval Facilities Engineering Service Center
PVC	polyvinyl chloride
QAPP	Quality Assurance Project Plan
RI	remedial investigation
RITS	Remediation Innovative Technology Seminar

## ACRONYMS AND ABBREVIATIONS (continued)

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RPM	Remedial Program Manager
SCAPS	site characterization and analysis penetrometer system
TAC	technical advisory committee
TAFB	Tyndall Air Force Base
TIO	Technology Innovation Office
VOC	volatile organic compound
WDS	Well Design Specification Software
WinOCPT	Win optical cone penetrometer



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*Technical material contained in this report has been approved for public release.*

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## 1.0 EXECUTIVE SUMMARY

During environmental site characterization, remediation, and compliance efforts, groundwater monitoring wells have served as the conventional tool-of-choice for accessing groundwater samples. Recently developed direct pushed (DP) technologies provide the means for collecting faster, less expensive groundwater samples when compared to conventionally drilled wells. The most extensive use of these cost-effective technologies, initially used almost exclusively as temporary installations for characterization purposes, have not been widely accepted for long-term monitoring at remedial action sites. For broad acceptance of DP well long-term monitoring applications, comparisons between conventionally drilled wells and DP wells needed to be conducted to validate these innovative approaches.

The purpose of this project was to rigorously compare the results of laboratory analyses conducted on samples obtained from DP wells to those obtained from wells installed utilizing conventional techniques (e.g., hollow-stem auger [HSA] wells). The demonstration consisted of these side-by-side comparisons followed by comprehensive statistical analyses over several years of quarterly monitoring. Five sites (located in New Hampshire, Delaware, California, Massachusetts, and Florida) comprised of various geologic regimes and contaminants of concern were included in this demonstration. Ultimately, the goal of this demonstration was to determine whether DP wells can yield representative data for long-term monitoring applications.

Comparisons between conventional drilled wells and DP wells consisted of evaluation of requirements for mobilization, installation, maintenance, removal, labor requirements for each step, performance metrics based on chemical and hydrogeologic representativeness, training requirements, ease of use considerations, appropriateness of innovative approach (e.g., lithologic restrictions where applicable), pertinent health and safety issues (e.g., less exposure for DP well installations), and overall costs. Hydraulic comparisons comprised of pneumatic slug and conventional aquifer tests were also performed in selected wells.

For the majority of the comparisons conducted during this demonstration project, management decisions were not impacted regardless of whether the well was installed by drilled or direct push methods. Project labor requirements tend to be lower for DP wells since well installation throughput rates are from two to five times higher than for drilled wells. Operator training for both drilled and DP well installation is similar; however, for some DP well installation systems, lower levels of technical expertise are typically required. Many states require licenses for well drillers, yet, the same is not generally true for operators of DP well installation equipment.

In most formations, DP is minimally intrusive and causes less disturbance of the natural formation than conventional drilling techniques, and often employs more mobile push platforms than conventional drilling vehicles. Worker exposure and industrial derived waste (IDW) disposal costs are reduced because little or no potentially contaminated drill cuttings are generated with direct push methods. Since many DP wells have a smaller diameter than traditional drilled wells, purge water volumes, sampling time, and indirect waste disposal costs are reduced for most sampling activities. When coupled with field screening and other site characterizing approaches afforded by direct push sensor and sampling techniques, DP well

installations afford expedited, comprehensive plume delineation while establishing infrastructure for long-term monitoring in a single mobilization.

A critical lesson learned stems from the observation that at very close proximities, chemical concentration values can vary significantly. This spatial heterogeneity can impact many other types of comparison projects where adjacent samples are evaluated. Temporal variability is also of significance and should be considered in trend analysis.

According to conservative estimates, cost savings for DP well installations range from approximately 32 to 68 percent. Highest percentage installation savings can be derived when using smaller diameter wells at deeper total depths. Assuming that 500 wells per state would be installed per year, the total anticipated Department of Defense (DoD) savings per year due to DP well installations ranges from approximately \$12 million to close to \$80 million. Since the majority of DP wells are less than 2 in [5.08 cm] in diameter, the low end DoD cost savings estimate is approximately \$20 million per year. Using these conservative estimates, industry savings could exceed \$200 million dollars per year with as few as 1300 DP wells per state per year. Life cycle cost savings associated with DP wells is significant, ranging from approximately 17 to 47 percent, and tends to be highest for smaller diameter wells installed to deeper depths

This comprehensive well comparison project constitutes the most thorough and conclusive comparison of conventional drilled wells and direct push wells to-date. With regards to performance, direct push wells performed at a level that warrants their acceptance as long-term monitoring devices for both chemical representativeness and hydraulic assessment categories. As a result of this effort, two American Society of Testing and Materials (ASTM) standards and an ITRC Technical Regulatory Guide have been completed and released for government and industry use.

## 2.0 BACKGROUND

During environmental site characterization, remediation, and compliance efforts, groundwater monitoring wells have served as the conventional tool-of-choice for accessing groundwater samples. A typical sequence of events in the life cycle of a contaminated site would include the discovery of a release, an initial source removal response, initial site characterization efforts, generation of a conceptual model, detailed site characterization efforts, remedial design, remedial system installation efforts, system performance monitoring, compliance monitoring, and site closure. Monitoring wells are generally installed at key steps in this sequence of events to define the extent of the contaminant plume, determine where and how fast it is migrating, select an optimal remediation method, evaluate the effectiveness of a remedial option, and to serve as long-term sample and data access conduits for compliance purposes. In most cases, critical decisions are based on data collected from wells that are installed using a drilling technique such as HSA.

Recently developed DP technologies provide the means for collecting faster, less expensive groundwater samples when compared to conventionally drilled wells. In addition, when compared to conventional applications, worker exposure to contaminants is significantly lower when installing DP wells and deploying sensor probes. The most extensive use of these cost-effective technologies has been for initial site characterization. DP wells, initially used almost exclusively as temporary installations for characterization purposes, have not been widely accepted for long-term monitoring (LTM) of contaminant and hydrogeologic properties at remedial action sites. For broad acceptance of DP well LTM applications, conducting comparisons between conventionally drilled wells and DP wells was needed to validate these innovative approaches. If comparable and representative DP well performance could be demonstrated, widespread regulatory acceptance of these cost-effective methods should be forthcoming.

Since groundwater monitoring wells are a major element of nearly all contaminated site characterization, remediation, compliance, and post-closure monitoring efforts, regulatory acceptance of DP wells can have a pronounced impact on overall cleanup costs throughout the DoD complex. The magnitude of the potential savings is significant considering that DoD is steward of nearly 25 million acres of land in the United States alone (U.S. DoD, 1995). Since the early 1980s DoD has acknowledged that nearly 30,000 contaminated sites exist in the United States, about half of which have not been cleaned up as of 2000 (U.S. EPA, 2000). Even if monitoring wells are installed at only 10,000 of the DoD sites awaiting cleanup, savings of just \$100 per well can quickly add up to millions of dollars saved overall. Savings in the tens of millions of dollars are more likely, given the extent of cleanup estimates and the fact that monitoring wells potentially will be used at every site. The Environmental Protection Agency (EPA) recently estimated that more than 350,000 hazardous waste sites would require restoration over the next 30 years at a cost of more than \$250 billion, with the DoD accounting for approximately 6,400 sites (U.S. EPA, 2004).

The demonstration consisted of side-by-side comparisons of the performance of conventional drilled wells and DP wells followed by comprehensive statistical analyses over several years of

quarterly monitoring. Five sites consisting of various geologic regimes and contaminants of concern were included in this demonstration.

## **2.1 OBJECTIVES OF THE DEMONSTRATION**

The purpose of this project was to rigorously compare the results of laboratory analyses conducted on samples obtained from DP wells to those obtained from wells installed utilizing conventional techniques (e.g., HSA wells). Hydraulic comparisons consisting of pneumatic slug and conventional aquifer tests were also performed in selected wells. Ultimately, the goal of this demonstration was to determine whether DP wells can yield representative data for LTM applications. Provided this is the case, the results will be used to convince regulators that DP wells should be accepted and their use encouraged throughout the industry.

## **2.2 REGULATORY DRIVERS**

The main regulatory concerns regarding the use of DP wells for long-term groundwater monitoring include the following:

- Most states have minimum annular sealing requirements based on drilled well specifications, yet DP wells have smaller annular spaces than conventional drilled wells, and are therefore not generally acceptable for LTM applications.
- Filter pack materials are either not used or are not based on grain size distribution of the formation in contact with the well screen section.
- Annular sealing may not be complete for prepackaged well screen devices and tremmied filter pack applications under certain geologic conditions.
- Until recently, chemical and hydrogeologic performance comparisons between DP wells and conventional drilled wells had not been demonstrated.

## **2.3 DEMONSTRATION RESULTS**

Key conclusions include the following:

- Most of the comparisons conducted during this demonstration project would not impact management decisions regardless of whether the well is installed by drilled or DP methods.
- DP wells perform comparably to drilled wells with respect to organic solute concentration measurements, inorganic concentration measurements, and hydraulic assessment capabilities.
- For LTM applications, DP wells are capable of providing representative chemical and hydraulic information.
- Adoption and regulatory approval of DP wells could lead to millions of dollars in savings for government and private entities.

As a result of this effort, two ASTM standards and an ITRC Technical Regulatory Guide have been completed and released for government and industry use. In addition, regulatory approval and issuance of waivers have become more commonplace. Through ongoing technology transfer vehicles such as ITRC workshops, Remediation Innovative Technology Seminars (RITS), and conference presentations, the results of this effort will be disseminated to regulators and users, ultimately leading to expedited and cost-effective well installation practices throughout the nation.

## **2.4 STAKEHOLDER/END-USER ISSUES**

End-users would include responsible parties, DoD, and other government and private entities. Key end-user and industry stakeholder buy-in is predicated on the regulatory acceptance of DP wells for LTM applications. Early on, the team recognized that design of a well comparison effort would benefit greatly from the knowledge, experience, and guidance of respected technical experts from private industry, government, and academia. In addition to the direct interactions with regulator-only organizations, a DoD Task Force on Direct Push Ground Water Monitoring Wells was convened during one of the preliminary studies that led up to the current project. This task force also met during the planning and execution stages of this demonstration. In addition, a technical advisory committee (TAC) consisting of leading industry and government experts in well applications was established for the Port Hueneme efforts preceding this demonstration. The TAC assisted with initial project planning, experimental design, and review of Dr. Mark L. Kram's original work plan for the Port Hueneme test cells. This team was reconvened for a workshop in December 2001 to assist with Phase I review (for all demonstration sites) and to help plan for Phase II design alterations. Expert technical oversight weighed heavily on the ultimate success of this demonstration, as regulatory buy-in was facilitated through credibility of the experimental design, execution, and data assessment activities supported through consensus.

In addition to design and execution of this well comparison demonstration, another critical project accomplishment included assistance with the development of two ASTM standards. These standards, entitled "Standard Guide for Installation of Direct Push Groundwater Monitoring Wells" (D6724) and "Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers" (D6725) were coauthored and edited by members of the project team. In addition to providing industry practitioners with guidance on the use and design of DP wells, these documents provide regulators with publications they can refer to as benchmarks for quality control. Furthermore, these standards can be used as procurement specifications to develop standard operating procedures and for training purposes.

Building on the success of the ASTM standards and initial well comparison technical report (Kram et al., 2001), pursuit of an ITRC Technical Regulatory guidance document through collaboration between project team members and regulators was initiated. The guide included case studies, statistical comparisons, and background information derived from this demonstration. This key regulatory document was released in March 2006 (ITRC, 2006), and an online ITRC DP well workshop has convened five times as of this writing. Of all the written products, this single document represents perhaps the most significant removal of technical and regulatory concerns and barriers, as it represents an implied regulatory approval of properly designed and installed DP wells.

During the course of this demonstration, several technical barriers were directly addressed to build support for regulatory approval. For instance, when the demonstration was initiated, regulators were concerned about DP wells that do not have filter packs. For wells that do have filter packs DP filter pack and screen designs did not conform to ASTM D5092 until recently. As a result, Kram and Farrar developed a software package to enable users to design wells in accordance with ASTM using soil classifications derived from penetrometer probe data (U.S. Patent 6,317,694). Since penetrometers can also be used to install DP wells, this allows for unprecedented customization of DP well designs with significant cost savings (compared to conventional soil sampling and grain size distribution assessment). While this software and concept is protected under a DoD patent, licensing to private industry partners is currently underway.

Hydraulic performance of DP wells was also a key source of regulatory concern. Regulators and industry users were not sure if hydraulic conductivity (K) measurements in DP wells matched similar measurements in conventional drilled wells. The hydraulic tests partially supported by this project illustrate that K values collected from highly permeable soils using slightly modified commercially available slug test equipment can be determined using DP wells. This component of the demonstration is significant for several reasons. It demonstrates to regulators that DP wells can be used for hydraulic measurements and that very short duration (e.g., less than 5 seconds) slug tests yield reproducible and comparable results to those measured in nearby drilled wells.

Future technology transfer plans include:

- Advertisement and presentation of ITRC workshop
- Continued release and dissemination of ITRC Technical Regulatory guide
- Utilization of DoD technology transfer vehicles such as conferences, RITS, Naval Facilities Engineering Service Center (NFESC) announcements, and final report dissemination
- Licensing of the Kram and Farrar well design software package
- Continued notification of DoD and industry users and DP service and materials providers.



### **3.0 TECHNOLOGY DESCRIPTION**

#### **3.1 TECHNOLOGY DEVELOPMENT AND APPLICATION**

DP techniques have been used to obtain stratigraphic information and soil engineering properties for several decades. DP is sometimes used as an alternative to drilling for the screening phase of a site characterization program and for temporary monitoring of remediation systems. DP approaches to site characterization and monitoring offer significant advantages by providing detailed, continuous subsurface stratigraphic information in real time while producing little or no drilling waste, thereby limiting worker exposure to hazardous materials and resulting in more rapid and discrete characterization efforts. Due to the high cost of drilling at contaminant sites, DoD and the Department of Energy (DOE) implement aggressive programs to develop chemical sensors and sampling methods for minimally intrusive direct push methods such as the cone penetrometer test (CPT) (Gildea et al., 1995; Montgomery et al., 1996; Farrington and Bratton, 1997; Kram, 1998, 2004, 2006a, 2006b; Lieberman et al., 1991, 1997, and 1998; McCall et al., 2006).

DP wells can be installed using either a static force system or a dynamic system. Static force systems consist of hydraulic ram units with a static weight of 20 to 30 tons (18,144 to 27,216 kg), while dynamic systems consist of a percussion hammer and hydraulic rams mounted on a smaller truck or track unit. Since the mid to late 1990s, DP has been used for installation of small-diameter (0.5 to 2.0 in [1.27 to 5.08 cm]) monitoring wells. A DP-installed monitoring well consists of a polyvinyl chloride (PVC) screen and riser that are advanced into the soil behind a dedicated drive point. After the well is installed, the drive point remains in place and serves as the bottom cap.

Details regarding installation of conventional HSA monitoring wells and the various DP well installations and designs are presented in the Final Report, Section 2.1.

Target contaminants monitored included methyl tertiary butyl ether (MTBE), petroleum hydrocarbons, and halogenated hydrocarbons.

#### **3.2 PROCESS DESCRIPTION**

As with drilled wells, DP well installations require comparable mobilization, clearance of the subsurface by means of geophysical methods coupled with utility maps, health and safety plans, and management of industrial derived wastes. Project labor requirements tend to be lower for DP wells since well installation throughput rates are two to five times higher than for drilled wells. Operator training for both drilled and DP well installations is quite similar; however, for some DP well installation systems, lower levels of technical expertise are typically required, as the installation equipment has been designed to be more intuitive for the operators. In fact, several academic and government research groups own their own DP well installation systems for this very reason. For more comprehensive drilled well requirements, these groups tend to outsource to organizations specializing in drilled well installation. Many states require licenses for well drillers. Although exceptions exist, the same is not generally true for operators of DP well installation equipment.

Approval of DP wells for LTM applications dictates that comparisons between conventional drilled wells and DP wells be conducted over an ample investigation period. Comparisons between conventional drilled wells and DP wells consisted of evaluation of requirements for mobilization, installation, maintenance, removal, labor requirements for each step, performance metrics based on chemical and hydrogeologic representativeness, training requirements, ease-of-use considerations, appropriateness of innovative approach (e.g., lithologic restrictions where applicable), pertinent health and safety issues (e.g., less exposure for DP well installations), and overall costs. In addition, regulatory standards are of significance, and the team approach for regulatory approval has been through ASTM standards generation, ITRC technical regulatory guidance and workshops, and state-by-state encouragement of DP well adoption for LTM applications. Successful implementation required an initial demonstration and recognition of the cost and technical benefits of DP wells, coupled with a comprehensive chemical and hydrologic comparison under various geological settings.

### **3.3 PREVIOUS TESTING OF THE TECHNOLOGY**

Several previous investigations have been completed to evaluate the use of DP well installations when compared to conventional (auger-drilled) wells (McCall, et al. 1997; McCall, 1999; Kram et al., 2001; British Petroleum and USEPA, 2002). Prior to this effort, no study focused on long-term data quality comparisons.

Beginning late in 1995, Applied Research Associates, Inc., under contract with the Air Force Research Laboratory (AFRL) began a program to compare the performance of DP and conventional monitoring wells for long-term groundwater monitoring of corrective action sites. Sites at Hanscom Air Force Base (AFB) and Hanscom Field in Massachusetts were selected for this initial study. A comprehensive work plan was prepared that included protocols for well installation, sampling, chemical analysis, and statistical comparisons, as well as a site-specific Health and Safety Plan (HASP) and Quality Assurance Project Plan (QAPP). DP wells were successfully installed adjacent to 43 existing conventional monitoring wells, creating matched well pairs installed to depths ranging from 13 to 65 ft (3.96 to 19.81 m). Screen lengths, elevations of screened intervals, and well diameters were matched as closely as possible in all pairs. Two rounds of sampling and analysis were completed, adhering strictly to a low-stress (low-flow) sampling protocol and evaluation of a suite of ten volatile organic analytes using EPA SW-846 methods. Paired data statistical tests were used to compare the performance of the two well types because of their ability to neutralize the influence of extraneous factors (e.g., location of the well pair within the contaminant plume, location with regard to local variation in the hydrogeology, and length and depth of the screened interval), which could vary from pair to pair but were assumed to have the same influence within each pair.

Statistical testing was conducted on nine analytes and five water quality parameters that were measured during purging of the wells for sample collection. The parametric Student's t-Test and nonparametric and Wilcoxon Signed Rank Test were applied to the data set, as appropriate, to test the null hypothesis that the mean of differences between paired observations was equal to zero.

With only one exception among all analytes and water quality parameters for which results were compared, the results showed no statistically significant difference between the performance of

the two well types. However, due to ongoing remediation efforts at the sites, the data generated during the study produced a large number of non-detects, which complicated the statistical analyses and decreased the number of observations in the statistical samples, thus limiting the power of the tests.

The EPA Technology Innovation Office (TIO) (Crumbling, 2000) conducted an independent review of the data. They concluded that the limited data set warranted additional sampling in more diverse geological settings. Thus, the current study expanded both the number of sampling events as well as the number and geologic diversity of sites involved.

Kram et al. (2001) conducted a number of detailed statistical analyses of water samples collected from clusters of colocated DP installed wells and conventional drilled wells. For each of the clusters, screens of equivalent lengths were installed at the same depths within the leading edge of the footprint of a solute MTBE plume located in Port Hueneme, California. Statistical comparisons of MTBE concentrations, major ions (including cations Ca, Na, K, Mn, Mg, Fe, and Ba; anions including SO<sub>4</sub>, NO<sub>3</sub>, Cl, and F), and water levels from the wells displayed no significant performance differences and no strong systematic variations attributed to well installation method or design. Using the analysis of variance (ANOVA) statistical approach, the authors concluded that spatial and temporal variations in chemical concentrations were considerably larger than variations associated with well type. The Port Hueneme DP well comparison site was incorporated into this project based on the previous observations, the unique and careful experimental design, the analyte type (MTBE), the hydrogeologic attributes of the site, and the personnel and infrastructure supported at the Port Hueneme National Environmental Technology Test Site (NETTS).

### **3.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY**

Table 1 lists several of the most important advantages and limitations associated with DP wells when compared to conventional drilled wells. Installing monitoring wells by conventional drilling methods is typically a time consuming and costly component of site characterization and monitoring. It is becoming widely recognized that DP well installations are significantly less costly than conventional drilled well installation approaches. In most formations, DP is minimally intrusive and causes less disturbance of the natural formation than conventional drilling techniques. DP methods are rapid and economical, and often employ more mobile push platforms than conventional drilling vehicles. Worker exposure and IDW disposal costs are reduced because little or no potentially contaminated drill cuttings are generated when wells are installed with direct push methods. Since many DP wells have a smaller diameter than traditional drilled wells, purge water volumes, sampling time, and indirect waste disposal costs are reduced for most sampling activities. Numerous innovations have been developed for groundwater monitoring through the direct push casings. For example, groundwater sampling from multiple zones can be conducted by employing packers or multilevel sampling ports. When coupled with field screening and other site characterization and field analytical approaches afforded by direct push sensor and sampling techniques, DP well installations afford expedited, comprehensive plume delineation while establishing infrastructure for LTM in a single mobilization. This is consistent with current industry trends towards employing a Triad approach to expedited site characterization.

**Table 1. Advantages and Limitations of DP Wells** (modified after ITRC).

<b>Advantages</b>	<b>Limitations</b>
<ul style="list-style-type: none"><li>• Inexpensive to install, replace and abandon</li><li>• Minimal waste “cuttings”</li><li>• Fewer well development wastes</li><li>• Rapid installation and site characterization</li><li>• Less worker exposure to contaminants</li><li>• Representative chemistry and field parameter measurements</li><li>• Improved landowner relations</li></ul>	<ul style="list-style-type: none"><li>• Not applicable when cobbles or consolidated materials are present</li><li>• Not accepted for LTM in most states</li><li>• Aquifer testing capabilities still debatable</li><li>• Well diameter limitations</li><li>• Pump diameter limitations</li><li>• Potential for higher turbidity in wells with no filter pack</li></ul>

The installation of DP wells is limited to unconsolidated soils and sediments including clays, silts, sands, and some gravels and cobbles, depending on the push equipment (e.g., heavy CPT trucks can push through harder materials than light trailer mounted rigs). Direct push methods cannot be used to install monitoring devices in consolidated bedrock and deposits containing significant cobbles and boulders, or in heavily cemented materials. Also, smaller diameter screens and risers do not allow for use of some conventional down-hole pumps for purging or sampling. Although state-by-state approval has been slowly on the rise, most states do not currently accept DP wells for LTM applications. The recent publication of the ITRC Technical Regulatory guide (ITRC, 2006), ongoing ITRC DP well Internet workshops, and forthcoming publication of the ESTCP Final and Cost and Performance Reports should lead to more rapid approval of the DP technology.

## 4.0 DEMONSTRATION DESIGN

### 4.1 PERFORMANCE OBJECTIVES

The demonstration objectives included performance comparisons between DP wells and conventionally drilled HSA wells with respect to specific field measurements and analyte concentrations. In addition, once statistical analyses were completed, and once these results suggested that DP wells perform comparably to conventional drilled wells, technology transfer was to be pursued through various activities including generation of ASTM DP well construction standards, an ITRC Technical Regulatory guide (comprising DP well construction descriptions, advantages and limitations of DP well technology, regulatory issues, and a summary of this field demonstration), development of regulatory variance guidance, national workshops, and presentations to conference attendees and regulatory representatives. Table 2 summarizes the type of performance objective, performance criteria, expected performance metrics, and whether the performance objectives were met.

**Table 2. Performance Objectives.**

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance Objective Met?</b>
Quantitative	Organic contaminant and inorganic analyte concentrations	Statistically significant agreement based on percent variability attributed to well type categorical factor; power of the statistic	Yes, with few exceptions
Quantitative	Field parameters	Statistically significant agreement based on percent variability attributed to well type categorical factor; power of the statistic	Yes, with few exceptions
Quantitative	Detect versus nondetect organic contaminant concentrations	Percent level of tolerance	Yes
Quantitative	Hydraulic property representation	Statistically significant agreement based on percent variability attributed to well type categorical factor; power of the statistic	Yes
Qualitative	Management decision consistency	Based on source zone, non-detect, and medium level of impact/concentration	Yes; decision consistent in all but one case believed to be due to heterogeneous distribution of non-aqueous phase liquid (NAPL)
Qualitative	Regulatory approval	Regulatory support via standards, technical regulatory guidance, variance approvals and guidance, and workshops sponsored by ITRC and Navy RITS	Yes, via ITRC Technical Regulatory Guidance, ASTM standards development and publications, ITRC and Navy-sponsored workshops, state approvals for DP wells and variances, and overwhelming industry support

Several challenges exist when trying to compare conventional wells to drilled wells. For instance, when using conventional drilled wells as experimental controls, the implication is that the conventional wells produce empirically accurate monitoring results. Because there is no universally accepted standard monitoring well or sampling method that produces an absolutely accurate representation of the groundwater, deriving an experimental control is not trivial. This is critical because the primary focus of this study is not to measure the accuracy with which samples from DP wells are representative of the groundwater, but rather to determine whether DP wells produce statistically equivalent results relative to conventionally drilled wells.

In addition to concerns regarding conventionally drilled wells serving as experimental controls, project partners recognized early in the demonstration that heterogeneity with respect to spatial distributions of solute contaminant concentrations and hydraulic conductivity could impart significant levels of variability in the observed results. In other words, if the concentration of an analyte obtained from the control well differed significantly from the concentration obtained from a DP well, the difference could be due to spatial distribution of the concentration in the subsurface and might not necessarily be the result of differences in well type. Since this heterogeneity is also dynamic, there can also be a temporal impact. For example, during the initial Phase I sampling rounds, water samples were collected and analyzed in triplicate. Within-well concentrations exhibited very low variability, while within-cluster comparisons exhibited statistically significant variability when comparison of the means was conducted using a conventional Student t-Test. If only one sampling round was evaluated, observers could conclude that the well types behave differently. Multiple sampling rounds were observed and, while the within-well variabilities remained low, within-cluster means for multiple rounds still exhibited high variability. However, there was no consistency regarding which well type exhibited higher mean values for all sampling rounds. One sampling event reflected a higher mean value in the drilled well representative, while another event exhibited a higher mean value in a DP representative. In order to best address these concerns, an ANOVA statistical approach was adopted, as categorical factors beyond simple well type differences can be incorporated into the data treatment and isolated and ranked based on their contribution to the total observed variability over time. For instance, variabilities associated with spatial heterogeneity, timing, and well screen length and position can be evaluated and weighed against variability due exclusively to well type (i.e., conventional versus DP).

When evaluated over several seasons, researchers can determine whether specific trends exist in the data. For instance, if one particular well type consistently exhibits a higher concentration than another over time, and if it is assumed that the spatial distribution of the subsurface solute concentration is dynamic and over time can exhibit relatively higher and lower concentrations depending upon when a sample event occurs, it may be possible to argue that the wells behave differently. However, if for some events the DP well type exhibits a higher concentration than the control well, then during other events, the control well displays higher concentration, this suggests that observed variability is due more to the subsurface spatial heterogeneity and dynamic characteristics of this heterogeneity than well type design. Furthermore, when considering relative range of concentrations observed in well pairs and clusters, whether or not a management remediation decision would change becomes a critical issue. If the trend in DP wells is that their values consistently lead to the same management recommendations (i.e., detect versus nondetect, above or below action levels, moderate concentration range versus high

concentration requiring remediation, etc.) as the corresponding control (i.e., conventional drilled) wells, even if there are statistically significant differences in the concentration values, since the management decision does not change, this is indeed significant, as it suggests that the DP wells meet critical performance goals.

In such a comparison, due to influences on the observations made which cannot be completely controlled, there is no absolute indication of sameness. Instead, the performance objective must be expressed in terms of the maximum acceptable degree of statistical uncertainty that sameness must exist. For this study, the performance objective is acceptance of the null hypothesis that the results from the wells do not differ at the 95% confidence level ( $\alpha=0.025$  for a two-tailed test)—that is, a p-value of greater than 0.05 would indicate success. In other words, if we can not reject the null hypothesis with better than 95% confidence, we must conclude there is no statistically significant bias introduced by substituting DP wells for conventional wells when conducting groundwater monitoring activities. A more detailed statistical description is presented in Section 4.3.1 of the Final Report.

## 4.2 SELECTION OF TEST SITES

The five sites chosen for this demonstration were selected to satisfy several criteria, including the following:

- *Representation of a variety of contaminants and geologic conditions.* Selected sites offered a broad range of common groundwater pollutants (e.g., benzene, toluene, ethyl benzene, xylene [BTEX], chlorinated solvents, and MTBE) and geological settings ranging from shallow, relatively less heterogeneous sandy aquifers to deep, heterogeneous glacial deposits. The specific contaminants and geologic features of each site are discussed in greater detail in Section 3.3 of the Final Report.
- *Representation of multiple regulatory domains.* Selected sites are located in five separate states and four EPA regions.
- *Proximity to study team members.* Selected sites allowed for direct participation and oversight by team members without incurring unnecessarily burdensome travel and logistical expenses. Three of the five selected sites were colocated with team member's duty stations.
- *Leveraging experimental apparatus and sampling support provided by other studies, past and present.* A prior study by the AFRL to assess DP well performance utilized 43 DP wells adjacent to conventionally drilled wells at Hanscom AFB. Eight of these existing well pairs were selected for use in this demonstration. A concurrent study by NFESC personnel at Port Hueneme included installation of eight multiple-well clusters, all of which were also used for this project. The Navy and Air Force leveraged funds to cover all sampling costs at Port Hueneme and at Dover AFB. During Phase I, selection of Tyndall AFB allowed Air Force team members stationed at the site to perform sampling with significant cost savings. For Phase II, Tyndall sampling was coordinated with support from Dover National Technology Site (DNTS) personnel.

### 4.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

Table 3 lists each facility, its state, geologic characteristics, depth to groundwater, analytes of concern, and the role of the facility.

**Table 3. General Test Site Characteristics.**

<b>Facility</b>	<b>Location</b>	<b>Geologic Character</b>	<b>Depth to GW (ft)</b>	<b>Analytes</b>	<b>Facility Role</b>
CRREL <sup>1</sup>	New Hampshire	Glaciofluvial and Glaciolacustrine	87 - 128	Chloroethenes	Army Cold Regions Research
DNTS <sup>2</sup>	Delaware	Marine Depositional	15 - 26	MTBE, BTEX, Chloroethanes	Air Force Base
NFESC <sup>3</sup>	California	Fluvial Deltaic	5 - 12	MTBE	Navy Port
HAFB <sup>4</sup>	Massachusetts	Glaciolacustrine	3 - 75	Chloroethenes, BTEX, Chlorobenzenes	Air Force Base
TAFB <sup>5</sup>	Florida	Marine Depositional	3 - 8	MTBE, BTEX, Chloroethanes	Air Force Base

<sup>1</sup> Cold Regions Research and Engineering Laboratory

<sup>2</sup> Dover National Technology Site

<sup>3</sup> Naval Facilities Engineering Service Center

<sup>4</sup> Hanscom AFB

<sup>5</sup> Tyndall AFB

### 4.4 PHYSICAL SETUP AND OPERATION

A detailed description of the physical setup and operation for each test facility is provided in the Final Report, Section 3.5.1.

### 4.5 SAMPLING/MONITORING PROCEDURES

A detailed description of the sampling and monitoring procedures for each test facility is provided in the Final Report, Section 3.5.7.

### 4.6 ANALYTICAL PROCEDURES

A detailed description of analytical procedures for each test facility is provided in the Final Report, Sections 3.5.7 and 3.6.



## 5.0 PERFORMANCE ASSESSMENT

### 5.1 PERFORMANCE DATA

A detailed presentation of the voluminous sampling and analytical results for each test facility is provided in the Final Report, Section 4. For most of the field parameters, inorganic analytes, and organic contaminants present at each facility, there does not appear to be a systematic bias that can be associated with DP well construction. For the few analytes where there were statistically significant differences (excluding a few questionable specific conductance values), the differences were generally not large in magnitude and most likely would not have impacted any management decision. One Tyndall AFB cluster did show a systematic difference, where a DP well consistently exhibited higher values than the rest of the wells in the cluster. However, it is believed that NAPL could be present and that preferential pathways combined with spatial distribution of the NAPL contributed to these findings. Statistical analyses of the data for volatile organic compound (VOC) concentrations near the detection limit also indicated that the performance of the DP and HSA wells was similar at each facility.

### 5.2 PERFORMANCE CRITERIA

Performance criteria and confirmation methods are presented in Tables 4 and 5, respectively. Additional details are presented in the Final Report, Sections 4.1 and 4.2.

**Table 4. Performance Criteria Description—Primary or Secondary.**

<b>Performance Criteria</b>	<b>Description</b>	<b>Primary or Secondary</b>	<b>Success Criteria</b>
Factors affecting technology performance	How well design impacts observed chemical and hydrological results	Primary	No difference compared to control
Versatility	Potential for use in applications other than LTM	Secondary	No difference compared to control
Hazardous materials	Potential for use at various types of contaminant sites	Primary	No difference compared to control
Process waste	Whether waste stream volumes are less or more than HSA	Secondary	Less waste compared to control
Reliability	Potential breakdowns of the equipment, sensitivity to environmental conditions	Secondary	No difference compared to control
Ease of use	Number of people required, level of skill required, installation time requirements, monitoring requirements	Primary	No difference or lower labor and time requirements compared to control
Long-term performance	Whether representative data can be collected for LTM applications	Primary	No difference compared to control

**Table 5. Expected Performance and Performance Confirmation Methods.**

<b>Performance Criteria</b>	<b>Expected Performance Metric</b>	<b>Confirmation Methods</b>
<b>Primary Criteria (Performance Objectives – Quantitative)</b>		
Technology performance	Statistically comparable chemical and hydraulic measurements; less than 10% of total observable error due to well design differences	Statistical comparison of chemical and hydraulic measurements
Hazardous materials	Statistically comparable chemical concentrations at various contaminant release sites; less than 10% of total observable error due to well design differences	Statistical comparison of chemical measurements
Ease of use	Comparable or lower labor and time requirements for DP wells	Documented experience from field demonstration
Long-term performance	Statistically comparable chemical measurements; less than 10% of total observable error due to well design differences	Statistical comparison of chemical measurements
<b>Secondary Criteria (Performance Objectives – Qualitative)</b>		
Versatility	Comparable chemical and hydraulic measurements	Documented experience from field demonstration
Process waste	Comparable or less waste volume than HSA installations	Documented experience from field demonstration
Reliability	Comparable equipment reliability and sensitivity to environmental conditions	Documented experience from field demonstration

### **5.3 DATA ASSESSMENT**

Demonstration results are presented in Table 4 and described in detail for each site in the Final Report, Section 4.3. All technology claims were verified. Furthermore, two regulatory standards were developed; an ITRC technical regulatory guide document was published; an ITRC workshop developed; and innovative hydraulic conductivity tests were demonstrated.

### **5.4 TECHNOLOGY COMPARISON**

This comprehensive well comparison project constitutes the most thorough and conclusive comparison of conventional drilled wells and DP wells to-date. With regards to performance, DP wells performed to a level that warrants their acceptance as LTM devices for both chemical representativeness and hydraulic assessment categories. Where applicable (e.g., in soils amenable to push tools), DP well installations can save significant amounts of time and cost when compared to conventional drilled wells. Additional details are presented in Section 4.3 of the Final Report.

## **6.0 COST ASSESSMENT**

### **6.1 COST REPORTING**

Actual demonstration-related well installation costs varied for each site. This was partly because previously installed wells at some sites, such as Hanscom, were used to leverage project costs. For these cases, existing wells were paired or clustered with new wells for comparison tests. For other sites, such as the Port Hueneme facility, a location was selected to specifically compare conventional drilled wells to DP wells. For the Hueneme test site, several site characterization steps were conducted prior to test cell design and well installation as part of the experimental design to limit variability and influence from external factors such as heterogeneous soil type distributions. For instance, piezocone pushes were advanced to identify candidate screen zones within the cells; soil cores were collected and analyzed to target high permeability zones for well screen depth ranges, which emphasized advective flux (versus diffusive flux); and grain size distributions were conducted to determine well design constraints in accordance with ASTM D5098. While this is the preferred approach to designing monitoring wells, contractors rarely follow these steps during production-oriented efforts. Therefore, this cost assessment focuses on costs that practitioners would encounter for installations of drilled and DP wells. Since installation costs are typically dominated by an initial expenditure for time and materials, a net present value evaluation will not be developed. Furthermore, discounted variable cost components such as sampling and analyses are considered comparable for both conventional and DP wells. Therefore, the cost assessment will emphasize elements within the well installation process and focus on the key cost differences between the two installation approaches.

Table 6 presents cost tracking categories and details. Cost considerations included expenses for mobilization, materials, labor, waste generation, per diem, well development, reporting, production rates (also a cost driver based on associated labor requirements), well rehabilitation, and well removal and decommissioning. Many of the costs incurred for drilled wells also apply for DP wells (e.g., surveying and certain material costs). The potential savings afforded by DP wells is typically dominated by the more rapid rate of installation, associated lower accrued labor expenses, and lower waste handling costs. Given a one-to-one comparison between drilled and DP well costs, the efficiencies of the DP well installation efforts lead to significant savings, especially when using smaller diameter DP wells. However, not included in this comparison is the critical fact that DP well installations can be part of a sequence of expedited direct push field activities conducted during a single deployment. For instance, use of a laser-induced fluorescence (LIF) probe for plume delineation, followed by a high-resolution piezocone for detailed three-dimensional modeling, can then be followed by customized DP well installations (based on the Kram and Farrar method) at optimized locations and depth ranges for LTM purposes. In contrast, drilled wells are typically not part of a Triad-based field analytical sequence but are more commonly installed independently as a single deployment to serve as an intermediate step between field screening and LTM strategies.

**Table 6. Cost Tracking.**

<b>Cost Category</b>	<b>Subcategory</b>	<b>Details</b>
Start-up costs	Site characterization	Typically preliminary but could be detailed
	Mobilization	Planning, contracting, personnel mobilization, transportation, permitting, site preparation
Operating costs	Operator labor	Time requirements
	Consumables, supplies	Fuel, water, etc.
	Residual waste handling	Volume differentials
	Offsite disposal	Based on volumes
	Waste manifesting	Based on volumes
	Well logging	Number per day
	Reporting	Time requirements
	Surveying	Time requirements
	Well development	Time requirements, waste generation
	Demobilization	Equipment removal, site restoration, decontamination, personnel demobilization
	Rehabilitation	Time requirements, waste generation
	Well removal	Time requirements, waste generation

Table 7 presents itemized cost assumptions used in the derivation of the cost comparisons for target depths of 20 ft, 50 ft, and 75 ft below grade. Baseline technology includes 2-in diameter rotary installed wells. Specifically, HSA drilled wells are installed via rotary methods. DP well cost assumptions are based on ¾-in diameter and 2-in diameter designs. For cost comparison purposes, all well screens are assumed to be 5-ft sections, and the examples are based on sets of 10 wells for each deployment set to the target depths specified. Many of the itemized costs are identical between DP wells and rotary wells. However, differences can arise when target depths, well diameters, and associated material costs are considered. The most significant differences contributing to DP well cost savings are due to the rapid installation rates (which impact labor and per diem cost totals) and the low waste generation volume and management requirements.

**Table 7. Itemized Cost Assumptions.**

	20'		50'		75'	
	DP Wells	Drilled Wells	DP Wells	Drilled Wells	DP Wells	Drilled Wells
Well diameter	2" and ¾"	2"	2" and ¾"	2"	2" and ¾"	2"
Maximum well depth	20' (6.1 m)	20' (6.1 m)	50' (15.24 m)	50' (15.24 m)	75' (22.86 m)	75' (22.86 m)
Mobilization (10 wells)	\$1,000	\$1,000	\$1,000	\$1,000	\$1,000	\$1,000
Average number installations/day	15	3	5	1	3	1
Riser pipe costs	\$1.75/ft (¾")	\$1.77/ft	\$1.75/ft (¾")	\$1.77/ft	\$1.75/ft (¾")	\$1.77/ft
	\$1.77/ft (2")		\$1.77/ft (2")		\$1.77/ft (2")	
Screen costs	\$2.85/ft (¾")	\$2.57/ft	\$2.85/ft (¾")	\$2.57/ft	\$2.85/ft (¾")	\$2.57/ft
	\$2.57/ft (2")		\$2.57/ft (2")		\$2.57/ft (2")	
Filter pack costs	\$10/ft (¾")	\$1.18/ft	\$10/ft (¾")	\$1.18/ft	\$10/ft (¾")	\$1.18/ft
	\$28/ft (2")		\$28/ft (2")		\$28/ft (2")	
Solid waste generation	0 drums	0.75 drums/well	0 drums	1.88 drums/well	0 drums	2.82 drums/well
Decon rinseate generated	0.2 drum/well (¾")	1 drum/well	0.5 drum/well (¾")	2.5 drums/well	0.75 drum/well (¾")	3.75 drums/well
	0.3 drum/well (2")		0.75 drum/well (2")		1.13 drum/well (2")	
Development water generated	20 gal/well (¾")	45 gal/well	50 gal/well (¾")	112.5 gal/well	75 gal/well (¾")	168.75 gal/well
	45 gal/well (2")		112.5 gal/well		168.75 gal/well	
Monument (flush)	\$33 ea. (8" skirt)	\$33 ea. (8" skirt)	\$33 ea. (8" skirt)	\$33 ea. (8" skirt)	\$33 ea. (8" skirt)	\$33 ea. (8" skirt)
Bottom cap	\$4.87/ft (¾")	\$5.50	\$4.87/ft (¾")	\$5.50	\$4.87/ft (¾")	\$5.50
	\$5.50 (2")		\$5.50 (2")		\$5.50 (2")	
Labor rate	\$1,000/day	\$1,000/day	\$1,000/day	\$1,000/day	\$1,000/day	\$1,000/day
Per diem (\$100 pp/day)	\$200/day	\$200/day	\$200/day	\$200/day	\$200/day	\$200/day
Grout	\$15	\$15	\$135	\$135	\$210	\$210
Foam seal	\$20 (¾")	N/A	\$20 (¾")	N/A	\$20 (¾")	N/A
	\$30 (2")		\$30 (2")		\$30 (2")	
Survey (10 well)	\$1,500	\$1,500	\$1,500	\$1,500	\$1,500	\$1,500
Well log	\$200	\$200	\$200	\$200	\$200	\$200
Well development	\$250 (¾")	\$500	\$500 (¾")	\$1,000	\$700 (¾")	\$1,500
	\$500 (2")		\$1,000 (2")		\$1,500 (2")	
Reporting	\$300	\$300	\$300	\$300	\$300	\$300

**Notes:** Well screens are assumed to be 5-ft sections. Calculation examples are based on sets of 10 wells for each deployment set to the target depths specified. Hardware costs are based on quotes from 2004.

When considering life-cycle costs, sampling and monitoring costs for DP and drilled wells should be very similar regardless of well depths. As can be seen in Table 8, small differences arise when considering liquid wastes associated with well rehabilitation efforts. Liquid wastes refer to well development water.

**Table 8. Itemized Well Rehabilitation and Removal Cost Assumptions.**

	20'		50'		75'	
	DP Wells	Drilled Wells	DP Wells	Drilled Wells	DP Wells	Drilled Wells
Labor rates	\$1,000/day	\$1,000/day	\$1,000/day	\$1,000/day	\$1,000/day	\$1,000/day
Average number labor days	2	2	2	2	2	2
Labor (remove)	2,000	2,000	2,000	2,000	2,000	2,000
Per diem (remove)	1,200	1,200	1,200	1,200	1,200	1,200
Labor (rehab)	4,000	4,000	8,000	8,000	10,000	10,000
Per diem (rehab)	1,200	1,200	1,600	1,600	2,000	2,000
Grouting	600	600	1,200	1,200	1,800	1,800
Grout rig (mob)	1,000	1,000	1,000	1,000	1,000	1,000
Solid waste	500	500	1,000	1,000	1,500	1,500
Liquid waste	800	2,000	800	2,000	800	2,000
Reporting	1,000	1,000	1,000	1,000	1,000	1,000
Totals 3/4"	\$12,300	-	\$17,800	-	\$21,300	-
Totals 2"	\$13,500	\$13,500	\$19,000	\$19,000	\$22,500	\$22,500

**Note:** Calculation examples are based on sets of 10 wells for each deployment.

## 6.2 COST ANALYSIS

The primary factors influencing costs associated with the installation of either DP or conventional wells are directly related to the generation of solid and liquid IDW and time considerations (Kram et al., 2001). Time is a significant consideration, especially if one uses the Kram and Farrar Well Design Specification (WDS) approach for well design, as it saves more than 50% of the installation time when compared to the sampling and grain size distribution via sieve analyses approach described and recommended in ASTM D5092. Furthermore, since one can install wells using CPT, well installations can be coupled to site characterization efforts, and well designs based on CPT soil classifications and WDS (which is based on ASTM grain size distributions) are optimized and therefore more cost effective, as there is a reduction in the location redundancies; each well location is based on specific data needs for that portion of the plume configuration; and probabilities for well failure are significantly reduced. Drilling spoils are essentially nonexistent for DP wells, with the exception of a small amount of soil removed while installing the surface seal and traffic or "Christy" box. Conversely, conventional well installations typically generate a significant volume of soil cuttings. For example, during the installation of the conventional wells at the Port Hueneme site, approximately 40 gal [5.35 ft<sup>3</sup>] of IDW were generated for each conventional well installed to a depth of 20 ft [6.1 m] below ground surface (bgs).

Costs are based on materials (riser pipe, screens, filter packs, bottom caps, traffic monuments, grout, sealing materials, etc.), depths (which impact hardware and labor costs), rates of installation for each approach (impacting total labor and per diem costs), waste generation, and labor costs (dependent upon installation rates, and survey, logging, development and reporting requirements). Many of the itemized costs are identical between DP wells and rotary wells. However, differences can arise when target depths, well diameters, and associated material costs are considered. The most significant differences contributing to DP well cost savings are due to the rapid installation rates (which impact labor and per diem cost totals) and the low waste generation volume and management requirements.

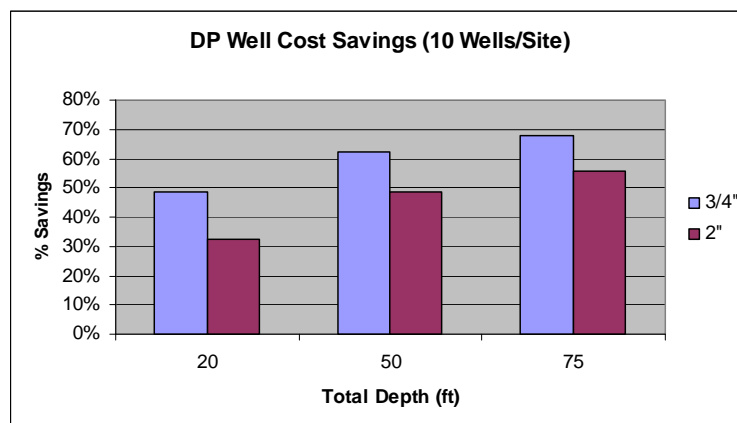
Life-cycle costs for DP wells were evaluated relative to conventional drilled well costs. As demonstrated in Tables 7 and 8, installation costs for 10 wells consisting of 5-ft screens represent the largest component of life-cycle cost differences between DP wells and drilled wells. Once the wells have been installed and developed, provided that low flow sampling methods are used and that well removal costs are similar, postinstallation and development DP and drilled well life-cycle costs are anticipated to be identical. Modest exceptions would be rehabilitation cost differentials between ¾-in DP wells and the 2-in wells (both DP and drilled), and grouting costs based on depths and hole diameter.

Conservative cost savings are illustrated in Table 9 (modified from Kram et al., 2003). Savings are derived based on total maximum well depth and well diameter. For each category, it was assumed that 10 wells were installed at each location and that all well screens were 5 ft [1.52 m] in length. Other considerations included costs for materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). According to these conservative estimates, cost savings for DP well installations range from approximately 32 to 68% (Figure 1). Highest percentage savings can be derived when using smaller diameter wells at deeper total depths. Users must consider that smaller diameter wells may not be appropriate for some applications (e.g., when a pump is to be used), that deeper wells can be more challenging for DP installation methods, and success will depend on the soil lithology and resistance to hydraulic or hammer installation techniques.

**Table 9. Cost Comparison Between DP and Drilled Monitoring Well Installations.**

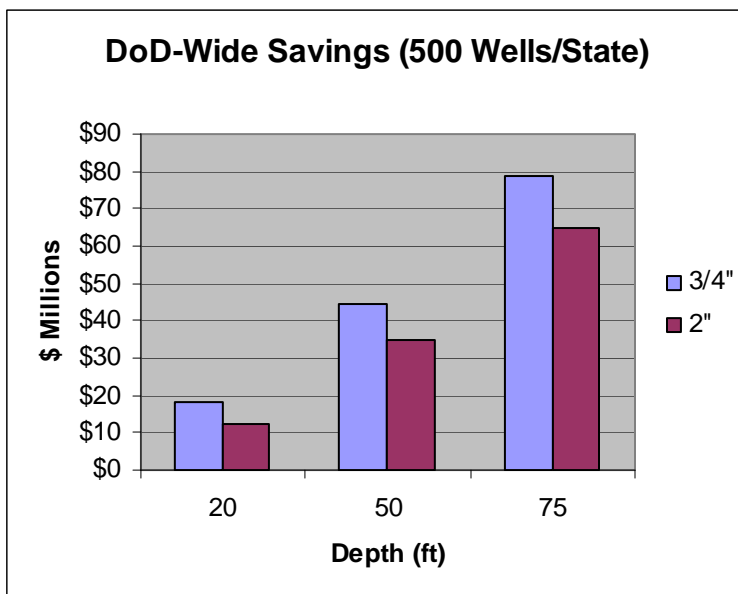
Total Depth	DP Wells		Drilled Wells	¾" Savings	2" Savings
	¾"	2"	2"	¾"	2"
20	\$7,799	\$10,254	\$15,146	48.5%	32.3%
50	\$10,664	\$14,575	\$28,418	62.5%	48.7%
75	\$14,876	\$20,543	\$46,393	67.9%	55.7%

**Note:** Estimates were derived assuming 10 wells per site, each designed with 5-ft (1.52 m) screens.



**Figure 1. Percentage Savings for DP Well Installations Based on Well Diameter and Depth.**

When accounting for the total DoD savings from DP well installations compared to conventional drilled wells, several assumptions were used. Since the number of DoD well installations per year is unknown, it was assumed that 500 wells per state are currently installed each year. The authors recognize that this value is not correct, and that it is perhaps overly conservative (e.g., actual number is probably much higher). For instance, at Naval Base Ventura Complex (NBVC) Port Hueneme alone, several hundred wells were installed per year for several years in a row. Regardless, Figure 2 displays the total anticipated DoD savings per year assuming 25,000 DP wells (or 500 per state) are installed per year. Cost avoidance estimates range from approximately \$12 million to close to \$80 million per year for DoD alone. Since the majority of DP wells are less than 2 in [5.08 cm] in diameter, the low end DoD cost savings estimate is approximately \$20 million per year. Using these conservative estimates, industry savings could exceed \$200 million dollars per year with as few as 1,300 DP well installations per state per year.



**Figure 2. Anticipated DoD Annual Savings by DP Well Installations for LTM.** (Values were derived assuming that 500 DP well installations would be completed per state each year.)

During the advisory committee workshop following Phase I of this demonstration, California regulators expressed concern about filter pack design in drilled wells. The primary issues have to deal with the fact that most DP wells are not designed in accordance with ASTM D5092, which requires sieve analyses to determine grain size distributions. Formation candidate screen zone grain size distributions dictate filter pack gradation and subsequently screen slot size. Interestingly, conventional wells are also required to meet these guidelines, yet rarely do installers follow these directives. Instead, in order to avoid the required sampling, sieve, and redeployment steps, drillers typically use a one-size-fits-all design that consists of a 20/40 sand pack tremmied to reside adjacent to a 0.010 in [.03 cm] slotted screen section. Silty sand and finer materials can readily pass through this configuration. As a result, well failure becomes possible, and often probable, especially in silt and clay rich formations.



To adequately address regulatory concerns regarding DP well design constraints, Kram and Farrar developed WDS software, which allows the user to determine the appropriate filter pack gradation and slot size requirements based on cone penetrometer soil type descriptors (U.S. Patent 6,317,694). Well design specifications can be determined in real time, effectively eliminating the need to collect a soil sample, reducing the time required in the field, and allowing for well design and installation during a single deployment. WDS is currently available on the Navy site characterization and analysis penetrometer system (SCAPS) system, as it has been integrated into the Win optical cone penetrometer (WinOCPT) data acquisition and processing package. When compared to conventional sampling and sieving approaches for proper well design, cost avoidance through use of WDS prior to DP well installation can be significant, often exceeding 50% savings. Primary savings drivers consist of reduction in field time and labor due to avoidance of need to collect samples, reduction in laboratory time due to avoidance of need to conduct sieve analyses, and reduction in need for additional remobilization step following laboratory results.

Assuming that well removal rates will be approximately 1.5 hr per well (for a total of 15 hr for a 10-well site) using the extraction method developed by Major and Osgood, life cycle-costs for 10 wells at a given site are presented in Table 10 for each of the three depths (i.e., 20 ft, 50 ft and 75 ft below grade). This table was developed assuming that one well rehabilitation/redevelopment effort was required and that well removal costs are identical for each well type (2 days total for each scenario). Installation costs (Table 9) were added to rehabilitation and removal costs (see Table 8 for assumptions) to derive the values presented in Table 10. Since most drillers do not currently properly design wells following ASTM recommended practices (e.g., sieve analyses followed by filter pack and slot selections) these estimates do not include additional cost savings afforded by the Kram and Farrar WDS approach. Life-cycle cost savings associated with DP wells is significant, ranging from approximately 17 to 47%, and tends to be highest for smaller diameter wells installed to deeper depths. Obviously, there are limitations to this generalization, as DP wells can be difficult to install to zones deeper than approximately 75 ft below grade unless formation conditions are ideal.

**Table 10. Life-Cycle Cost Comparison Between DP and Drilled Monitoring Wells.**

Total Depth	DP Wells		Drilled Wells	3/4" Savings	2" Savings
	3/4"	2"	2"	3/4"	2"
20	\$20,099	\$23,754	\$28,646	29.8%	17.1%
50	\$28,464	\$33,575	\$47,418	40.0%	29.2%
75	\$36,176	\$43,043	\$68,893	47.5%	37.5%

**Note:** Estimates were derived assuming costs for 10 wells per site, including installation, rehabilitation, and removal.

It is important to note that the cost difference between DP and drilled wells would most likely be much greater when used in production mode (as opposed to a research effort or using the cost avoidance assumptions employed in this projection). For instance, the number of DP wells installed would be much higher for a conventional project (e.g., up to 15 DP wells per day in the same geologic setting), whereas the maximum number of HSA wells team members have installed is 4 per day at the same site. The difference in daily production rate would lead to greater economies of scale on a large remedial investigation (RI) project than are evident from this small demonstration study. Furthermore, when coupling the well installation efforts with

other DP site characterization technologies, such as plume delineation, cost benefits for DP wells are even more significant than those represented in this section.

### **6.3 COST COMPARISON**

Conservative cost savings are illustrated in Table 9 and Figure 1 (modified from Kram et al., 2003). Savings are derived based on total maximum well depth and well diameter. For each category, it was assumed that 10 wells were installed at each location and that all well screens were 5 ft [1.52 m] in length. Other considerations included costs for materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). According to these conservative estimates, cost savings for DP well installations range from approximately 32 to 68% (Figure 1). Highest percentage installation savings can be derived when using smaller diameter wells at deeper total depths. Assuming that 500 wells per state would be installed per year, the total anticipated DoD savings per year as a result of DP well installations range from approximately \$12 million to close to \$80 million per year (Figure 2). Since most DP wells are less than 2 in [5.08 cm] in diameter, the low end DoD cost savings estimate is approximately \$20 million per year. Using these conservative estimates, industry savings could exceed \$200 million per year with as few as 1,300 DP wells per state per year. Life-cycle cost savings associated with DP wells is significant, ranging from approximately 17 to 47%, and tends to be highest for smaller diameter wells installed to deeper depths (Table 10).

Users must consider that smaller diameter wells may not be appropriate for some applications (e.g., when a pump is to be used), that deeper wells can be more challenging for DP installation methods, and success will depend on the soil lithology and resistance to hydraulic or hammer installation techniques. However, when DP well installations are appropriate, significant reduction of worker exposure to hazardous materials can be realized, and time requirements can be reduced relative to conventional drilled wells.

Furthermore, additional cost savings are anticipated when one implements the Kram and Farrar WDS method, when DP well installations are coupled with production efforts such as initial or supplemental site characterization, and when conducting hydraulic assessments using pneumatic slug tests.

## **7.0 IMPLEMENTATION ISSUES**

### **7.1 COST OBSERVATIONS**

Key factors affecting project costs relative to original estimates included mid-project transfer of management duties, the need for a Phase II effort to address outstanding regulatory and statistical requirements for LTM applications, and redirected technology transfer efforts. In particular, initial technology transfer goals included technology certification through the California EPA CalCert program. The CalCert program was terminated by the State of California, leaving team members with fewer regulatory approval options. Decisions were made to develop two ASTM standards (approved as ASTM D6724 and D6725) and to work with ITRC to develop a Technical Regulatory Guidance document. These successful endeavors are proving to be flagship approaches, whereby other innovative technologies can follow similar paths for regulatory acceptance.

Site-specific conditions will dictate whether DP wells can and should be used. For instance, the soil must be penetrable for successful installation. In addition, well diameter must be appropriate for use. If a pump will be required to obtain samples or contain a plume, it is critical that users select appropriate well diameters to accommodate these purposes.

Additional cost savings are anticipated when one implements the Kram and Farrar WDS method, when DP well installations are coupled with production efforts such as initial or supplemental site characterization, when more than 10 wells are required to complete a project, and when conducting hydraulic assessments using pneumatic slug tests. In addition, DP tooling is under continuous improvement, reducing labor requirements (e.g., one-person installations), streamlining installation efforts, and ultimately increasing throughput and production rates.

### **7.2 PERFORMANCE OBSERVATIONS**

Section 3 of the Final Report describes performance with respect to acceptance criteria for each quantitative and qualitative performance objective set forth in the demonstration plan. With very few exceptions, project objectives were met. The only exceptions included a few examples where statistically significant differences in analyte concentrations were observed. However, for at least a few of these exceptions, NAPL presence is suspected, which would impart spatial influence over the distribution of solute in the vicinity of the test cells.

### **7.3 SCALE-UP**

When moving from demonstration-scale to full-scale implementation, additional cost savings are anticipated based on the fact that while most contaminant release sites typically require 10 to 15 monitoring wells, it is common to observe more than 20 wells at moderate to large sites requiring LTM. In general, for larger sites, cost savings through implementation of DP wells becomes higher. Since several types of DP well installation rigs currently exist in the public and private sector, equipment availability should not pose a problem.

## **7.4 OTHER SIGNIFICANT OBSERVATIONS**

While release of the ITRC guidance document represents regulator willingness to accept the use of DP wells for LTM applications, convincing state regulators to adopt these concepts in their formal well requirements and recommendations will require time and a focused outreach effort. The ITRC workshop should help alleviate much of this challenge. However, incorporation into state or federal regulatory guidelines may still be needed to encourage acceptance on a national level. Some communities (e.g., the County of San Diego, California) have produced guidance to assist potential users with waivers for DP well installations. This model provides an interim solution to DP well LTM use as state and local DP regulations are updated on a state-by-state basis. ASTM standards developed as part of this project would not only help in this regard but could also be used as procurement tools for contracting purposes.

## **7.5 LESSONS LEARNED**

One of the most critical lessons learned stems from the observation that at very close proximities, chemical concentration values can vary significantly. This spatial heterogeneity can impact many other types of comparison projects where adjacent samples are to be evaluated. Temporal variability is also of significance. However, when properly addressed, this can offer advantageous benefits through trend analysis and recognition that observed variabilities among technologies may actually be due to temporal and spatial categorical factors. As always, appropriate statistical analyses must be employed in order to draw the correct conclusions. For instance, if scatter plots are used for comparing DP and conventional well concentrations over time, correlations are observed to be relatively low (e.g., less than 0.7). However, ANOVA reveals that the variabilities observed are due almost entirely to temporal and spatial categorical factors, and variability associated with well type differences is low. Furthermore, DP wells and conventional wells should yield data that would lead to consistent long term site management and monitoring systems.

## **7.6 END-USER ISSUES**

Project team members have been recognized for their efforts on this project. As a result, their efforts to serve as advocates for these innovative approaches have proven to be effective. This is exemplified by the multiple invitations for speaking engagements, consultations with specific state regulators who are overseeing Remedial Project Manager (RPM) projects, and invitations to serve as experts on panels for this and other innovative approaches. Base environmental managers have also presented site tours to university groups such as the Bren School of Environmental Science and Management, DoD visitors, and conference attendees. Project managers have adopted these technologies, local regulators are beginning to allow for variances, and some have even allowed Dr. Kram waivers on permits where DP wells were used above the primary water-bearing beneficial use zone. ASTM standards and the ITRC technical regulatory guidance document completed as part of this project should lead to end-user and regulatory acceptance throughout the nation. Development and implementation of an RITS module will lead to further acceptance and use of DP wells within DoD.

## **7.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE**

Regulatory drivers consist of state well requirements, bulletins, and guidelines. Early on in the project, well installation efforts required well permits. Since this was a demonstration project, a waiver was granted. At the Port Hueneme site, Dr. Kram identified a coherent nonconductive layer at the base of the “semi-perched” aquifer. Based on this finding and the generation of the ASTM standards for DP wells, Dr. Kram was allowed to install Phase II wells with a permit exemption. Dr. Kram has attempted to convince the California state regulators to alter their well bulletin. However, to-date, funding for these alterations has not yet been approved. As a result, regulators in San Diego County, along with Navy SCAPS team members and members from the project team, crafted guidance to enable DP well users to obtain a waiver for the long-term use of DP wells.

Perhaps of most significance is the acceptance of DP wells by regulators who have become familiar with the ITRC Technical Regulatory guidance document for DP wells. Among all technology transfer mechanisms, this appears to be the most effective, as regulators throughout the nation are now able to grant waivers and permits for DP wells without fear of confrontation with other regulatory bodies and entities. Through workshops, future publications, and dissemination of the ITRC guidance, team members will encourage regulators to approve the use of DP wells for LTM applications, and perhaps even alter their state guidance bulletins.

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## 8.0 REFERENCES

- ASTM D 6724, Standard Guide for Installation of Direct Push Ground Water Monitoring Wells.
- ASTM D 6725, Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers.
- Bartlett, S.A., G.A. Robbins, J.D. Mandrick, M.J. Barcelona, W. McCall, and M.L. Kram, 2004, Comparison of Hydraulic Conductivity Determinations in Direct Push and Conventional Wells, Naval Facilities Engineering Service Center Technical Report, TR-2252-ENV, October, 2004, 88 pp.
- Bianchi, J.C., and S.P. Farrington, 2000. Direct Push Monitoring Point Assessment Hanscom Air Force Base, Applied Research Associates, Inc.
- Bower, H., and R. C. Rice, 1976. A Slug test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells, Water Resources Research, Vol. 12, No. 3, 1976, pp. 423-423.
- British Petroleum and USEPA, 2002. Monitoring Well Comparison Study: An Evaluation of Direct Push versus Conventional Monitoring Wells, 80 pp.
- Butler, J.J., Jr., J.M. Healey, G.W. McCall, E.J. Garnett, and S.P. Loheide II, 2002. Hydraulic Tests with Direct-Push Equipment, Ground Water Journal, Association of Ground Water Scientists & Engineers, Volume 40, Number 1, January-February, pp. 25-36.
- Conover, W.J., 1980. Practical Nonparametric Statistics, John Wiley & Sons, NY.
- Crumbling, D., 2000. Innovations in Site Characterization Case Study: Direct Push Comparison For Hanscom Air Force Base, US EPA Technology Innovation Office, March, 2000.
- Driscoll, F.G., 1986. Groundwater and Wells. Johnson Filtration Systems, Inc., St. Paul, MN, 5512.
- Farrington, S.P., and W.L. Bratton, 1997. Measuring Fuel Contamination Using Cone Penetration Testing and High Speed Gas Chromatography, Final Report to U.S. Department of Energy, Morgantown Technology Center, Morgantown, WV, February 1997.
- Feller, W., 1968. An Introduction to Probability Theory and Its Applications, Volume I, John Wiley & Sons, NY.
- Gildea, M.L., W.L. Bratton, and J.D. Shinn, 1995. Demonstration and Evaluation of the Air Force Site Characterization and Analysis Penetrometer System in Support of Natural Attenuation Initiatives, Under Contract F0863 5-93 -C-0020, SETA Subtask 8.01.1, Report to Air Force Armstrong Laboratory, Tyndall AFB, FL, February 1995.

- Grant, C. L., T. F. Jenkins, and A. R. Mudambi, 1996. Comparison Criteria for Environmental Chemical Analyses of Split Samples Sent to Different Laboratories, Special Report 96-9, CRREL, May, 1996.
- Hald, A., 1952. Statistical Theory with Engineering Applications, John Wiley & Sons, NY.
- Hvorslev, M. J., 1951. Time Lag and Soil Permeability in Ground-Water Observations, Waterways Experiment Station, Corps of Engineers, U.S. Army, Bulletin No. 36, 1951, p. 50.
- Iman, R.L., 1974. Use of a t-statistic as an Approximation to the Exact Distribution of the Wilcoxon Signed Ranks Test Statistic, Communications in Statistics, v. 3.
- ITRC, 2006. The Use of Direct Push Well Technology for Long-term Environmental Monitoring in Groundwater Investigations, Technical Regulatory Guidance, March, 2006, 71 pp.
- Kram, Mark L., 1998, Use of SCAPS Petroleum Hydrocarbon Sensor Technology for Real-Time Indirect DNAPL Detection, Journal of Soil Contamination, Vol. 17, No. 1, 1998, p. 73-86.
- Kram, Mark, D. Lorenzana, J. Michaelson, and E. Lory, 2001. Performance Comparison: Direct-Push Wells Versus Drilled Wells, Naval Facilities Engineering Service Center Technical Report, TR-2120-ENV, January 2001, 55 pp.
- Kram, Mark, D. Lorenzana, J. Michaelson, W. Major, L. Parker, C. Antworth, and T. McHale, 2003. Direct-Push Wells Prove Effective for Long-Term Ground Water Monitoring, Waterwell Journal, v. 57, No. 4, April 2003, p. 16-18.
- Kram, Mark L., Arturo A. Keller, Steve M. Massick, and Leroy E. Laverman, 2004. Complex NAPL Site Characterization Using Fluorescence, Part 1: Selection of Excitation Wavelength Based on NAPL Composition, Soil and Sediment Contamination: an International Journal, March/April, v. 13, No. 2, pp. 103-118.
- Kram, Mark L., Gary Robbins, Renduo Zhang, Lanbo Liu, and Norm Jones, 2006. Detailed Hydraulic Assessment Using a High-Resolution Piezocone Coupled to the GeoVIS, in Proceedings of the North American Environmental Field Conference, Tampa, FL.
- Kram, Mark L., 2006. DNAPL Characterization Methods and Approaches: Performance and Cost Comparisons, in The Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring, D. M. Nielsen, Editor, CRC Press/Taylor & Francis Publishers, Boca Raton, FL, p. 473-516.
- Lieberman, S.H., G.A. Theriault, S.S. Cooper, P.G. Malone, R.S. Olsen, and P.W. Lurk, 1991. Rapid Subsurface In Situ Field Screening of Petroleum Hydrocarbon Contamination Using Laser Induced Fluorescence Over Optical Fibers, Proceedings of the Symposium on Field Screening Methods for Hazardous Wastes and Toxic Chemicals, U.S. EPA, Washington, DC, 1991, pp. 57-63.



- Lieberman, S.H., D.S. Knowles, J. Kertesz, P.M. Stang, and D. Mendez, 1997. Cone Penetrometer Deployed In Situ Video Microscope for Characterizing Subsurface Soil Properties, Proceedings of the Symposium on Field Screening Methods for Hazardous Wastes and Toxic Chemicals, Air and Waste Management Association, Pittsburgh, PA, 1997, pp. 579-587.
- Lieberman, S.H., G.W. Anderson, V. Games, J. Costanza, and A. Taer, 1998. Use of a Cone Penetrometer Deployed Video-Imaging System for In Situ Detection of NAPLs in Subsurface Soil Environments, Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Ground Water Association, Westerville, OH, 1998, pp. 384-389.
- McCall, W., S. Stover, C. Enos, and G. Fuhrmann, 1997. Field Comparison of Direct Push Prepacked Screen Monitoring Wells to Paired HSA 2" PVC Wells. In Superfund XVIII Conference Proceedings, Volume 2. p. 647-655. E.J. Krause and Assoc., Washington, D.C.
- McCall, W., 1999, Field Comparison of Paired Direct Push and HSA Monitoring Wells, in Natural Attenuation of Chlorinated Solvents, Petroleum Hydrocarbons, and Other Organic Compounds, April 19-22, 1999, Alleman and Leeson, eds.
- McCall, W., D.M. Nielsen, S.P. Farrington, and T.M. Christy, 2006. Use of Direct-Push Technologies in Environmental Site Characterization and Ground-Water Monitoring, in Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring, Second Edition, 2006, pp. 345-471, D.M. Nielsen ed.
- Royston, J.P., 1982. An Extension of Shapiro and Wilk's W Test for Normality to Large Samples, Applied Statistics, v. 31.
- San Diego County, 2004. SAM Manual, Appendix B, Monitoring Well/Boring Permit and Standards, Section D: Small Diameter Well Variance Guideline, San Diego, CA, pp. B-20 to B-36.
- SAS Institute Inc., 1990. SAS Procedures Guide, Version 6, 3rd Ed., Cary, NC, 1990.
- Shapiro, S.S. and M.B. Wilk, 1965. An Analysis of Variance Test for Normality (complete samples), Biometrika, v. 52, no. 3 and 4, p. 591-611.
- State of California, 1981. California Department of Water Resources Bulletin 74-81: Water Well Standards: State of California, December 1981, 92 pp.
- Steel, R.G.D., and J.H. Torrie, 1990. Principles and Procedures of Statistics, McGraw-Hill, NY.
- Walpole, R., and R. Myers, 1978. Probability and Statistics for Engineers and Scientists, Macmillan, NY.
- U.S. Department of Defense, 1995. Defense Environmental Restoration Program, Annual Report to Congress for Fiscal Year 1995.

- U.S. Environmental Protection Agency, 2004. Cleaning Up the Nation's Waste Sites: Markets and Technology Trends, 2004 Edition; <http://www.epa.gov/superfund/news/30years.htm>.
- U.S. Environmental Protection Agency, 2000. Superfund: 20 Years of Protecting Human Health and the Environment, U.S. EPA Publication EPA 540-R-00-007.
- U.S. Environmental Protection Agency, 1996. Drinking Water Regulations and Health Advisories, Office of Water, Washington, DC, February 1996.
- U.S. Environmental Protection Agency, 1989. Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities, Office of Solid Waste Management Division, Washington, DC, February, 1989.
- U.S. Environmental Protection Agency, 1988a. Guidance for Conducting Remedial Investigations/Feasibility Studies Under CERCLA.
- U.S. Environmental Protection Agency, 1988b. Laboratory Data Validation Functional Guidelines for Evaluating Organic Analyses, Hazardous Waste Site Evaluation Division, Washington, DC.
- U.S. Environmental Protection Agency, 1986. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846, 3rd Edition.
- U.S. Patent 6,317,694, November 13, 2001, Method and Apparatus for Selecting a Sand Pack Mesh for a Filter Pack and Well Casing Slot Size for a Well, Mark L. Kram and Jeffrey A. Farrar.

## APPENDIX A

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